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Coupling Watershed Erosion Model with Instream Hydrodynamic-Sediment Transport Model: An Example of Middle Rio Grande

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1. Introduction

1.1 Study area and background

The Middle Rio Grande (MRG) is located in Central New Mexico (Figure 1 insert). As one of the most historically documented rivers in the United States, MRG is under constant supervision from regulatory agencies such as the U.S. Bureau of Reclamation (USBR) and U.S. Army Corps of Engineers (USACE) (Albert, 2004). MRG was historically characterized as an aggrading sand bed channel with extensive lateral bank movement, which caused serious flooding problem (Richard et al., 2005; Sixta, 2004). To improve channel conveyance and reduce flood risks, channelization works, levees, and dams were built to control sediment concentrations in the MRG and to inhibit bed aggradation.

The reach of this study is the diversion dam reach of the MRG, which spans from Alameda Blvd bridge to Paseo Del Norte bridge including the Calabacillas Arroyo (Figure 1). The diversion dam has been built about 1,500 feet south of the Alameda Bridge on the river. The city of Albuquerque is diverting water from the Rio Grande with the operation of this diversion dam to supplement the city's drinking water supply. Previously, all of their drinking water needs were supplied by groundwater wells. There are two USGS gauges located at the Alameda Blvd bridge and Paseo Del Norte bridge, respectively. The Calabacillas Arroyo is located in Northwestern Bernalillo and South-central Sandoval counties. The Calabacillas Arroyo is a steep, relatively straight channel with a large width-to-depth ratio and has significant potential for lateral and vertical instability. The channel, consisting of a Bluepoint loamy fine sand, drains a watershed with a total area of approximately 220 square kilometers and enters the MRG about 70 km downstream of Cochiti Dam. The Calabacillas Arroyo watershed is primarily underlain by the sand-rich Santa Fe Formation that is comprised of the basin fill sediments (fluvial, paludal, and lacustrine) of the Rio Grande basin (Simons, Li and Associates, 1983). In addition to the Calabacillas Arroyo watershed, the arroyo also discharges water from portions of the Black's Arroyo watershed due to contributions from the concrete-lined Black Diversion Channel, the only significant tributary of the Calabacillas Arroyo. The drainage area of the Black's Arroyo is approximately 25 square kilometers (Mussetter, 1996).

Flows in the Calabacillas Arroyo are ephemeral, responding only to local rainfall events. In this climatic region, approximately half of the precipitation occurs between July and October, often in heavy thunderstorms. There is potential for significant floods due to the scale and characteristics of the drainage area, and high precipitation events can lead to flash floods and significant sediment transport events (Chen et al., 2009). Swinburne Dam was completed in 1991 at Unser Boulevard across the Calabacillas Arroyo. The structure was constructed as both a stormwater detention facility and to mitigate the recurrence of the sediment plug at the Rio Grande through sediment trapping. Multiple grade control structures have also been placed in the Calabacillas Arroyo to manage channel incision. Currently, many of these structures have been significantly or fully submerged by sediment deposition from upstream. Quantifying sediment transport capacity affected by these structures is a need for local watershed management (personal communication with the Albuquerque Metropolitan Arroyo Flood Control Authority - AMAFCA).

1.2 Purpose of the study

The purpose of this study is to examine how the sediment input from the Calabacillas Arroyo, a tributary to the Middle Rio Grande affects the geomorphology in the main stream. As shown in Figure 2, a huge alluvial fan at the confluence has resulted from sediment outflows from the Calabacillas Arroyo during extreme flood events, which has reduced the main MRG channel width by approximately one half and significantly affected the sediment transport capacity of the stream. The large amount of sediment input breaks the sediment balance in the MRG and may result a number of hydrological and ecological consequences, such as the channel geometry, flood frequency and changes in aquatic habitat. Quantitatively predicting geomorphic changes in the mainstream MRG considering the tributary sediment input will greatly improve the understanding of hydrological processes for the entire stream-watershed system, and provide better guidance for future management practices. Despite the great challenge to the research, the goal was achieved by simulating the watershed, tributary and mainstream as an interconnected system.

2. Models and approach

Output from a physically based watershed erosion model has seldom been used as input to a channel sediment transport model in a previous study (Beven, 2001). Aiming at accurately assessing the sediment transport in forested watershed, Conroy et al. (2006) has coupled the Water Erosion Prediction Project (WEPP) model (Flanagan et al., 1995) with the National Center for Computational Hydrodynamics and Engineering's One-Dimensional (CCHE1D) hydrodynamic-sediment transport model (Wu et al., 2004).

Our approach is to conduct a combined modeling study to investigate the mainstream geomorphic changes with sediment input from the tributary during typical storm events. The whole study will include three major parts: the watershed sediment yield, the tributary sediment transport, and the main stream sedimentation. Firstly, the Kinematic Runoff and Erosion Model (KINEROS2) model was used to estimate sediment yield from the Calabacillas Arroyo watershed during different storm events. Secondly, analysis of sediment transport in the channel was performed using the HEC-RAS program developed by Hydraulic Engineering Center (HEC) of U. S. Army Corps of Engineers. Thirdly, the main stream sedimentation process was modeled with a two-dimensional sediment transport program CCHE2D. Each model will be briefly described as follows.

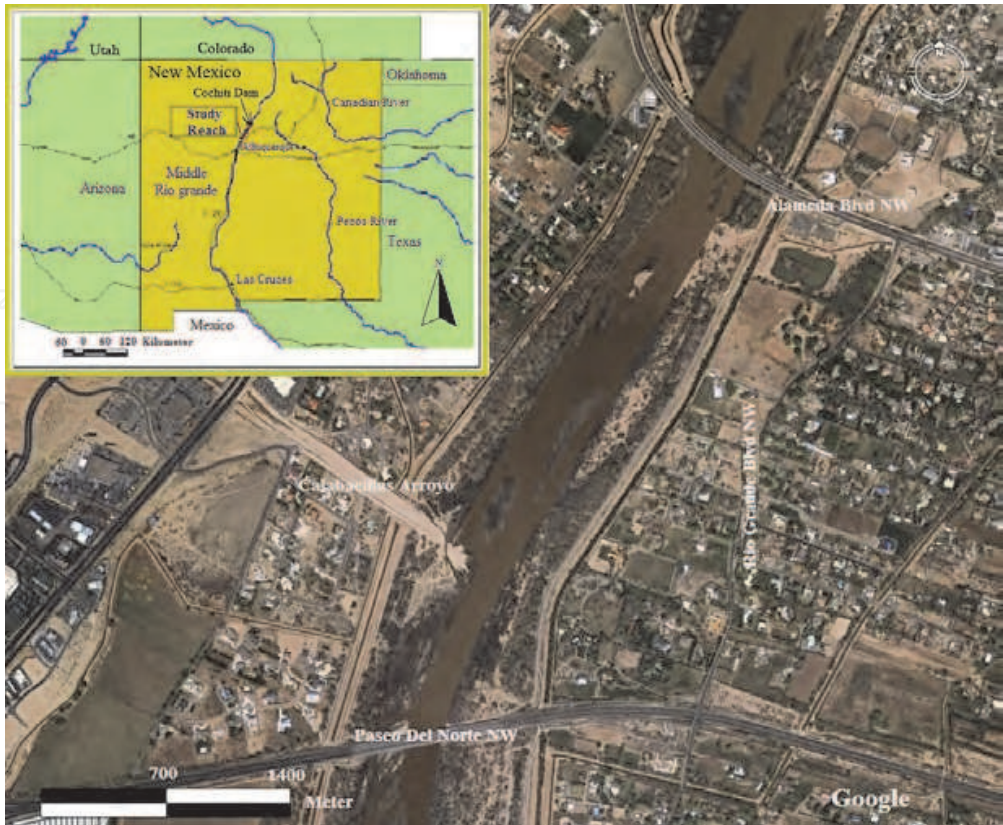


Fig. 1. Map of the Study Site.



Fig. 2. Aerial photograph of the sediment plug on August 19, 1988 (AMAFCA).

2.1 KINEROS2 model

The KINEROS2 model has undergone long term development in the US Department of Agriculture, Agriculture Research Service (USDA-ARS). It describes the physical processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds and uses physically-based approach to simulate dynamics of short duration rainfall-runoff processes in watersheds. In this model, a watershed is represented by a series of planes (hill-slopes) and channels. Interception, infiltration and overland flows are simulated for planes to generate runoff, and channel routing is simulated to transport runoff to the outlet of the watershed with the consideration of transmission loss. Infiltration on planes as well as in channels is modeled using a three-parameter general infiltration model (Parlange et al., 1982). Technical details can be found from the website <http://www.tucson.ars.ag.gov/kineros/>. The model is included in the Automated Geospatial Watershed Assessment Tool (AGWA) package and is made available to public as an ArcGIS extension to simplify the data processing and modeling process (<http://www.tucson.ars.ag.gov/agwa/>).

2.2 HEC-RAS model

HEC-RAS program was developed by Hydraulic Engineering Center (HEC) of U. S. Army Corps of Engineers. The latest HEC-RAS model provides a module for sediment transport analysis. This model was designed for modeling one-dimensional sediment transport, and can simulate trends of scour and deposition typically over periods of years or alternatively, for single flow events. For unsteady flow events, it segments the hydrograph into small time periods and simulates the channel flow for each time interval assuming a steady state flow in the whole channel. The non-equilibrium sediment transport approach included in the module makes the sediment transport process more realistic. The sediment transport potential is computed by grain size fraction so that the non-uniform sediment can be represented more accurately. The model can be used for evaluating sedimentation in fixed channels and estimating maximum scour during large flood events among other purposes (Hydrologic Engineering Center, 2008). The HEC-RAS sediment transport module provides the option of several different sediment transport functions, thus users can select the most appropriate function according to the site conditions. This module also has the ability to limit degradation to specified elevations/depths at individual cross-sections which allows for the representation of Grade Control Structures (GCS) in the arroyo for the modeling study.

2.3 CCHE2D model

CCHE2D is an integrated software package for two-dimensional simulation for analysis of river flows, non-uniform sediment transport, morphologic processes, coastal processes, pollutant transport and water quality developed at the National Center for Computational Hydro-Science and Engineering at the University of Mississippi. These processes in the model are solved using the depth integrated Reynolds equations, transport equations, sediment sorting equation, bed load and bed deformation equations. The model is based on Efficient Element Method, a collocation approach of the Weighted Residual Method. Internal hydraulic structures, such as dams, gates and weirs, can be formulated and simulated synchronously with the flow. A dry and wetting capability enables flow simulation on complex topography. There are three turbulence closure schemes in the model, depth-averaged parabolic, mixing length eddy viscosity models and k- ϵ model. The

numerical scheme can handle subcritical, supercritical, and transitional flows (NCCHE, 2009). The applicability of CCHE2D for the study reach has been proved by Chen et al. (2007).

2.4 Modeling procedure

The modeling system described in this article uses an aggregated approach to model watershed sediment yield, stream sediment transport, and bedform change. As shown in figure 3, the HEC-1 and KINEROS2 results provide the flow and sediment boundary conditions (BCs) for HEC-RAS Calabacillas Arroyo channel model, respectively. The HEC-RAS model result is further used as the tributary flow and sediment boundary conditions (BCs) for the CCHE2D main stream model. The CCHE2D model for the main stem MRG also needs the input data of flow and sediment from the main stream. Using this interconnected system, we are able to examine how the sediment input from the tributary affects the geomorphology in the main stream of the MRG.

3. Data & model preparation

3.1 Calabacillas arroyo watershed sediment yield

For the watershed sediment yield analysis we need the topographic data, soil data, and land cover data. All of these data sets can be downloaded from the public available internet sites. A ten-meter digital elevation model (DEM) data used for watershed delineation and 2001 land cover data were obtained from the U. S. Geological Survey (USGS) via internet. SSURGO soil data was obtained from the U. S. Department of Agriculture Soil Data Mart site. Using the topographic data, we can delineate the watershed via the AGWA extension in the ArcGIS environment. The soil data and land cover data were used to parameterize the model, which can be done within the AGWA interface. Meteorological data for different storm events were shapefiles of precipitation-frequency grids from NOAA. These grids are based on high-resolution (~800 m) NOAA Atlas 14 precipitation frequency estimates that were calculated from the analysis of partial duration series (see hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html). The computed sediment yield totals from KINEROS2 were used as the sediment boundary conditions in the HEC-RAS analysis.

3.2 Calabacillas arroyo channel sediment transport

Arroyo channel hydraulics and sediment transport conditions were simulated with HEC-RAS. The first step of this study is to generate cross sections to represent the channel geometry. This was done using the high resolution (2-ft contour) digital terrain model (DTM) data provided by the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) within the HEC-GeoRAS software for ArcGIS environment developed by HEC, USACE (<http://www.hec.usace.army.mil/software/hec-ras/hec-georas.html>). The study reach in Calabacillas Arroyo ranges from Swinburne Dam to the confluence of the arroyo at the MRG. A total of 114 cross sections were extracted from the DTM data (see Figure 4). Among others, 17 cross sections designate the approximate locations of existing grade control/soil cement structures. Locations of these structures were estimated using engineering drawings provided by AMAFCA. The elevations of the bases of the grade control structures were determined from engineering drawings and entered into HEC-RAS as minimum elevations (below which the channel bed will not be eroded at those cross sections).

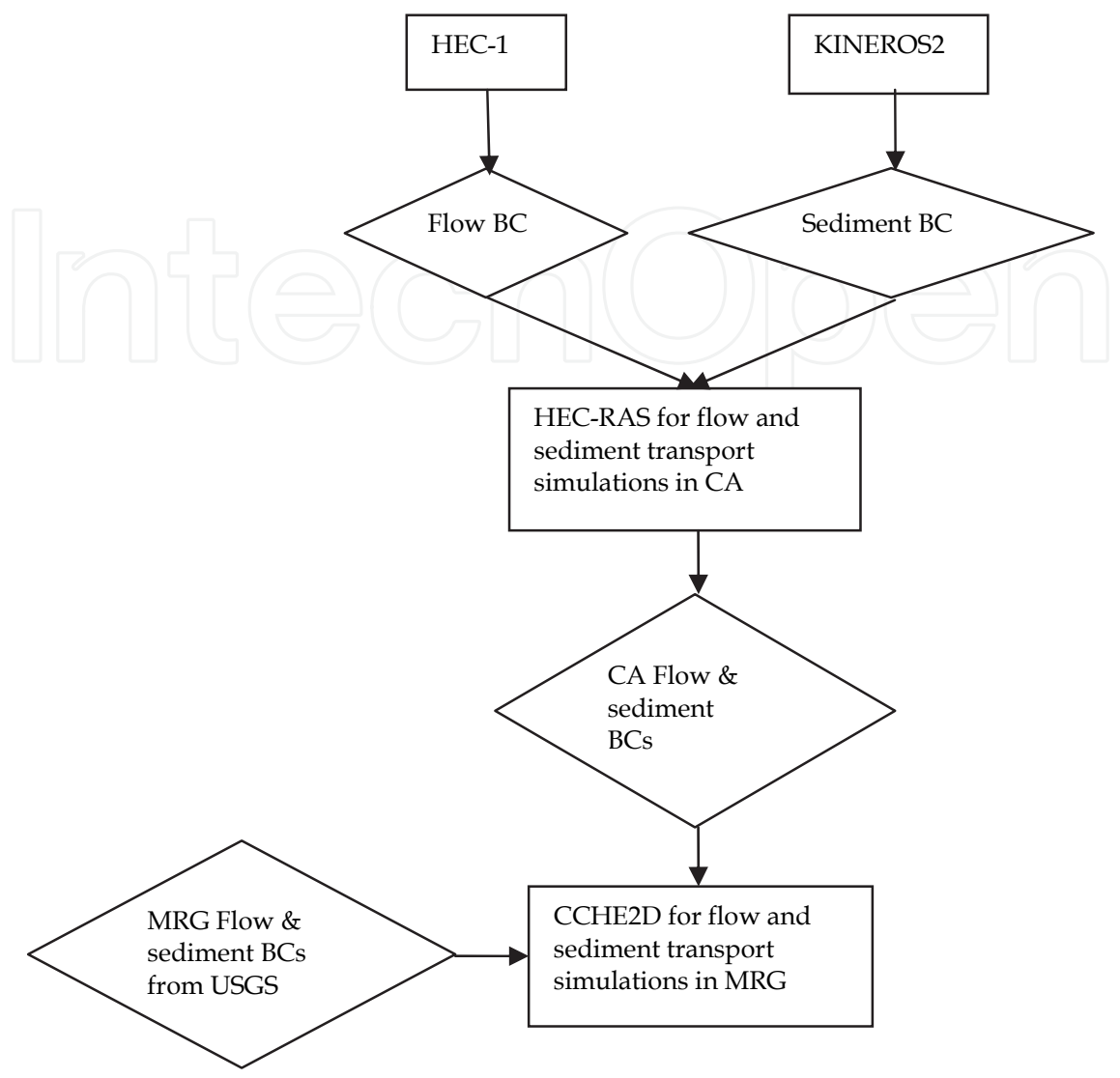


Fig. 3. Flowchart for modeling system.

HEC-1 hydrograph data for existing conditions from a previous study for AMAFCA was used to create the upstream flow boundary condition in HEC-RAS. The flow data from HEC-1 was on five-minute intervals. During the modeling study, we have used both the original data and the small interval high density data down to 30 second interpolated by HEC-RAS to test the sensitivity of the HEC-RAS sediment module to time step. The peak flow values for the 100-year, 25-year, and 10-year 24-hour storms were calculated as 12,302 cfs, 7,921 cfs, and 5,391 cfs, respectively. The downstream flow boundary condition was set to normal depth, which was based on the friction slope (0.0105 ft/ft) calculated from the cross sections in the most downstream 400 feet of the channel.

Sediment bed gradation characteristics for the channel bed were based on sediment sampling data provided in the Calabacillas Arroyo Prudent Line Study and Related Work (Mussetter Engineering, Inc., 1998). Figure 5 shows the gradation curves of five different samples along the Calabacillas Arroyo channel. While the locations are not provided here, the samples are numbered starting from most downstream to most upstream. Based on Figure 5, about 60-90% bed particles belong to sand (smaller than 2mm).



Fig. 4. Image from HEC-GeoRAS showing the cross sections (green lines) and channel centerline (blue line) drawn over the study area. The green and blue contours in the bottom-right show the DTM elevation data processed within ArcGIS.

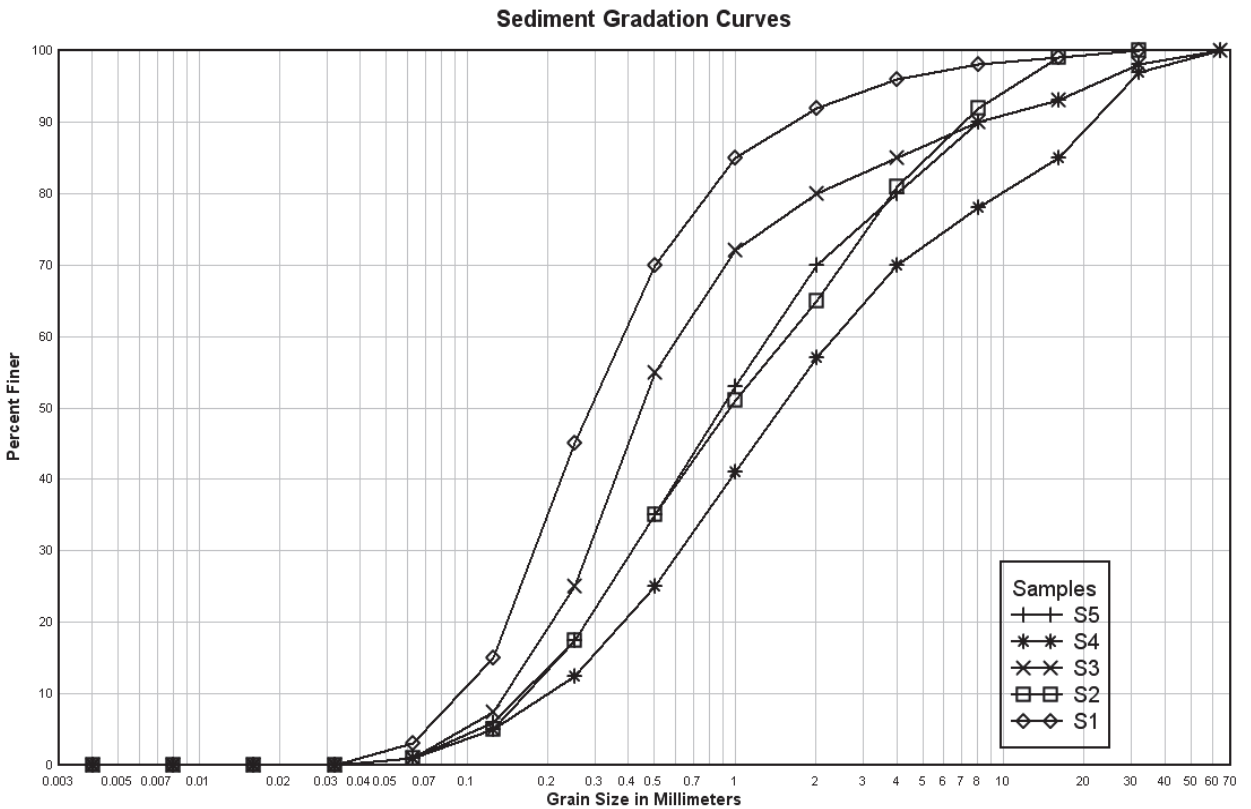


Fig. 5. Sediment particle size distribution curves used in the Calabacillas Arroyo sediment transport study. Based on sediment sampling from Mussetter Engineering, 1998.

It is very difficult to select the most appropriate sediment transport function without field data verification. In the study, we made the choice based on literature and our modeling experiences. We initially selected three transport functions: Engelund-Hansen (EH), Meyer-Peter-Muller (MPM), and Yang(Chien and Wan, 1999). The EH function calculates the total sediment load and is most appropriate for sandy rivers with substantial suspended load. The EH function was developed from flume data and has been found to fairly consistent with field data when tested. The MPM function is a bedload transport method. In the MPM function, transport rate is proportional to the difference between the mean shear stress acting on a sediment grain and the critical shear stress. This method has been widely accepted for coarse sediment rivers. The Yang method is based on the theory that unit stream power is the dominant factor for sediment concentration or unit sediment discharge. The method has been supported by both field measurements and flume experiments in many studies.

3.3 Main stream sediment transport

A 2-D computational mesh was generated based on channel topographic data extracted from a digital contour map which was produced combining the cross section data from HEC-RAS model (downstream of the diversion dam) and measurement by AMAFCA (arroyo) and University of New Mexico (upstream of the diversion dam). Bed material gradations were obtained from textural analyses of in-Channel Cored Samples taken by Sandia National Laboratories (SNL). The original data include bed material gradation in five layers at 27 sampling sites along the reach. For the simplification and requirement by CCHE2D, we reduced it to three layers and applied an averaged bed material gradation for each layer.

The final computational mesh covered the entire study reach with 400 cross sections in the main stem of MRG and 40 cross sections in the tributary (Calabacillas Arroyo). Each cross section in the main stem has 45 computational nodes, while each tributary cross section has 7 nodes.

4. Modeling results

4.1 Calabacillas arroyo watershed sediment yield

We used KINEROS2 model to calculate the sediment yield of the watershed for 100-year, 25-year, and 10-year recurrence interval 24-hour storms. The model calculated sediment yield at each element and obtained the total sediment yield at the watershed outlet for the whole watershed (with an area of 20077.16 hectares) by calculating transport of sediment from all elements through channel network. The result is summarized in the following table.

Event	Yield (kg/hectare)	Yield (kg)
10year-24hour	0.0036	73.24
25year-24hour	0.6886	13,825.14
100year-24hour	333.41	6,693,968.04

Table 1. Sediment yield estimates from KINEROS2 for the entire watershed.

Figure 6 shows an example of the calculated spatial distribution of sediment yield from KINEROS2 model for the 100-year event. The results disclose the spatial distribution and the major source of the flow and sediment generated from the watershed during a large storm event. The simulation may provide useful information for future watershed management. Those sediment yield results were used as the input sediment load for HEC-RAS simulations.

4.2 Calabacillas Arroyo channel sediment yransport

Table 2 shows the cumulative sediment load near the confluence of the Calabacillas Arroyo from different design storm events from the HEC-RAS simulations. The cumulative sediment load at the second most downstream cross section was recorded for each simulation. The most downstream cross section was held at a constant elevation (zero bed change) in the boundary condition file. Model runs were made with the selected transport functions, design storm events, and for two different conditions, with and without the presence of grade control structures (GCS). The presence or absence of GCS did not lead to large changes in the totals. In some cases, the presence of GCS led to slightly larger sediment totals as compared to runs without GCS.

In the HEC-RAS sediment transport analysis of the Calabacillas Arroyo, three transport functions were used: Engelund-Hansen (EH), Meyer-Peter-Muller (MPM), and Yang. The choice of transport function strongly impacted the totals. The EH transport equation provided the highest totals and the MPM equation provided the lowest totals. The highest total produced, 284,259 tons (US short tons), was with the EH transport function with GCS for a 24-hour, 100-year storm. The lowest total, 2,430 tons, was produced with the MPM transport function without GCS for a 24-hour, 10-year storm. For the sake of save channel design, EH function with GCS was adopted for the current study. Figure 7 shows the Calabacillas Arroyo channel bed change after 100-year event when using EH transport function with GCS. Alternative erosion and sediment deposit were simulated along the Calabacillas Arroyo channel. Since the upstream sediment boundary was far below the equilibrium condition, serious bed scouring was calculated at the Calabacillas Arroyo inlet.

Function		100year	25year	10year
EH	No GCS	275,928	172,754	120,384
	With GCS	284,259	175,318	118,929
Yang	No GCS	164,184	111,935	86,323
	With GCS	167,549	109,421	87,073
MPM	No GCS	4,490	3,094	2,430
	With GCS	4,489	3,097	2,440

Table 2. Cumulative sediment load at the most downstream cross section in US short tons.

4.3 Main stream bedform change

The CCHE2D model for the main stem Rio Grande needs the input data of flow and sediment from both the main stream and the tributary Calabacillas Arroyo. In this modeling

work, the equilibrium sediment boundary was adopted for the main stream MRG, while the sediment input from the tributary Calabacillas Arroyo was calculated by HEC-RAS model using EH function with GCS (see Section 4.2).

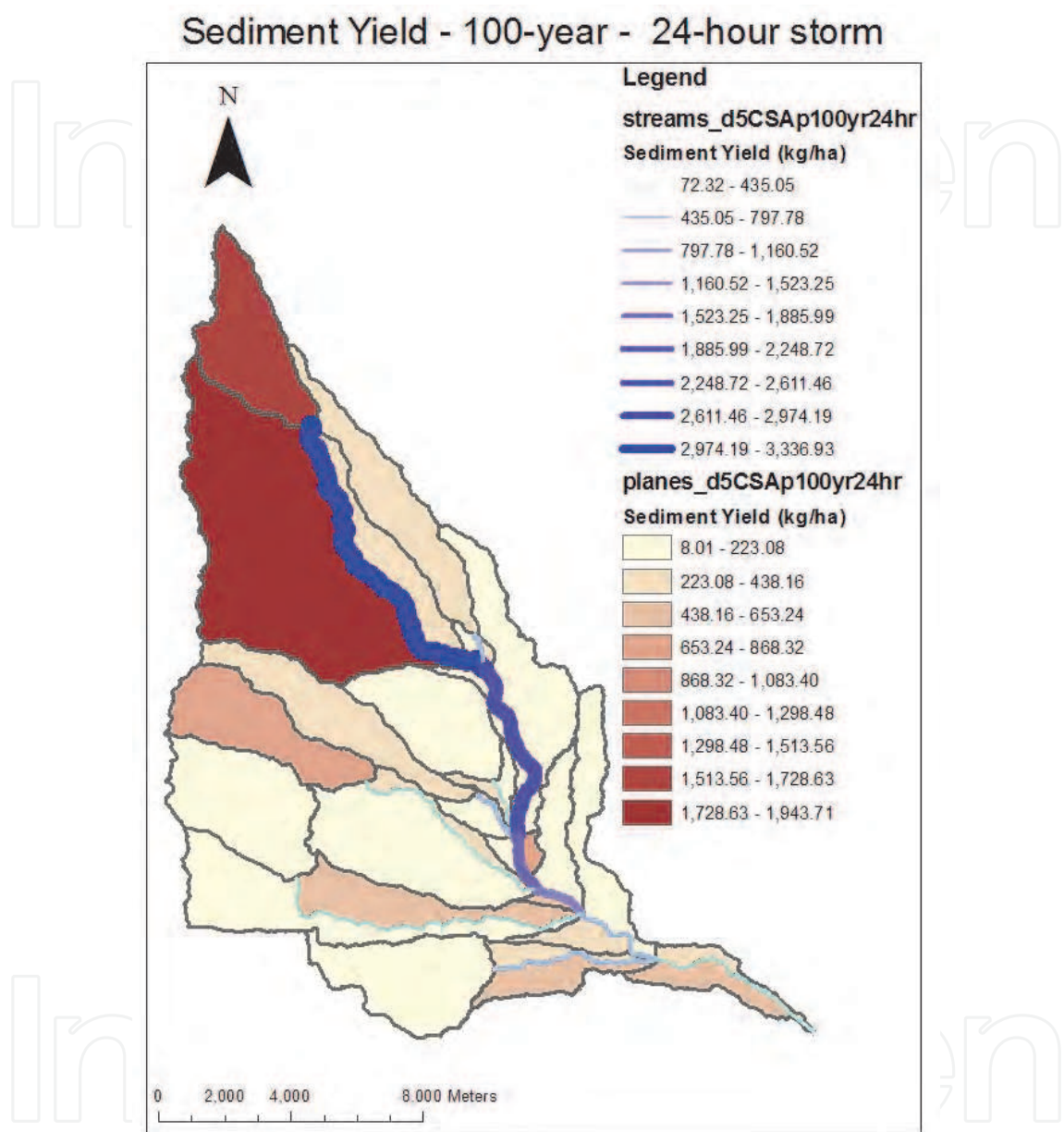


Fig. 6. Sediment yield results from KINEROS2 model for 100-year event.

Figure 8 shows the bed elevation changes at two extreme scenarios: (a) 100-year flood occurs in the MRG with synchronous 10-year storm in the tributary; (b) 100-year storm occurs in the tributary with based flow in the MRG. Figure 8a represents a favorable condition for river maintenance: although the whole channel system was an aggrading system in the past (Chen et al., 2007), sedimentation was minimal under those conditions. In contrast, Figure 8b represents the worst case: a heavy rainstorm has been restricted to the upper watershed of the Calabacillas Arroyo which results in a 100-year storm in the tributary and huge sediment load, while the flow in the main stem of MRG remains

around 25m³/s (base flow). In the case of Figure 8b, a great amount of sediment has settled around the confluence area which indicates that base flow in the main stem does not have enough hydraulic power to transport the deposited sediment to downstream reaches. Most serious deposition (around 1m) is located a bit downstream of the confluence, while depositing depths elsewhere are less than 0.5m. In addition, it could be observed that sedimentation in Figure 8b traces toward the upstream along the right bank for several hundred meters, which is believed due to the ponding effect produced by excessive downstream aggradation.

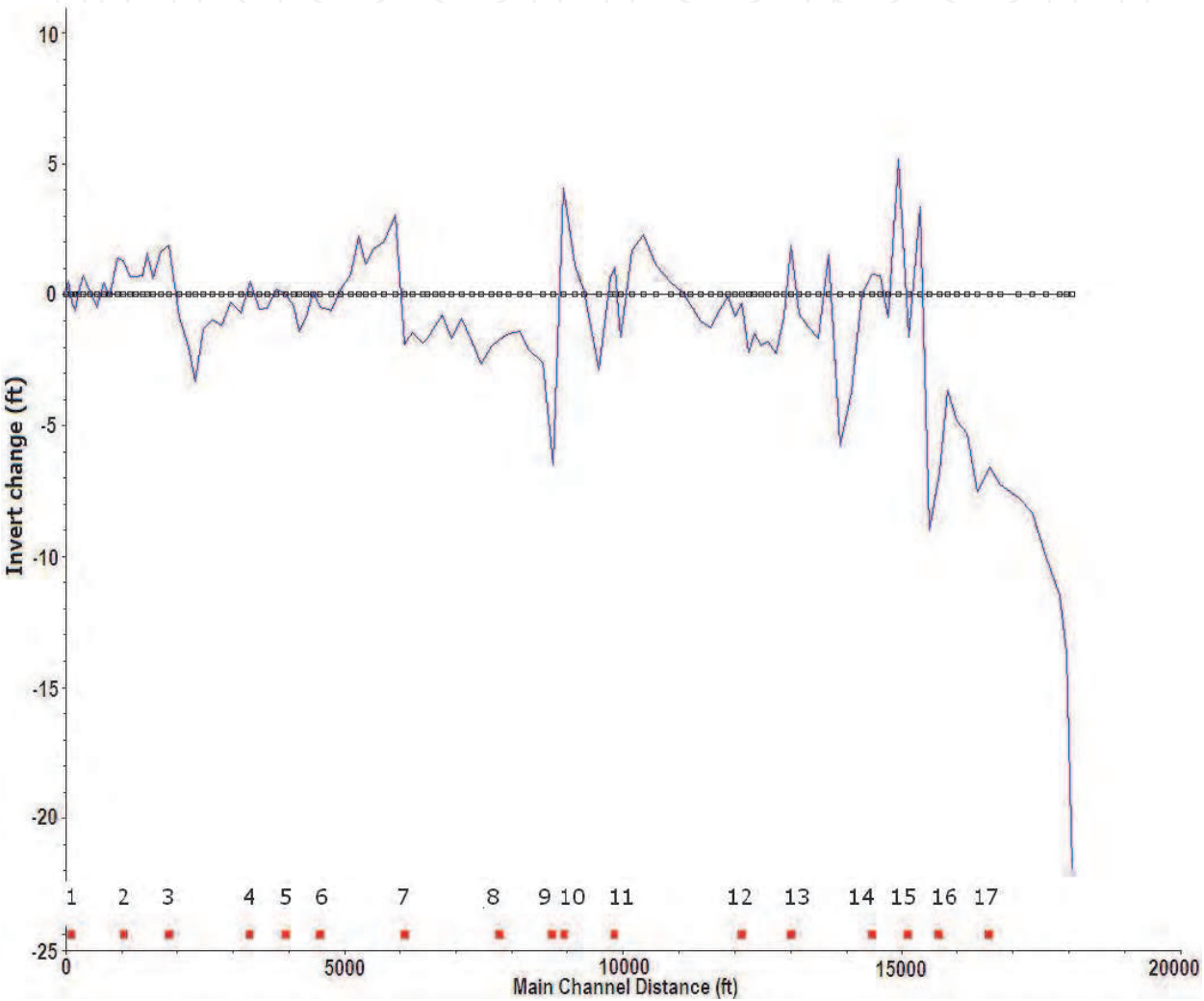


Fig. 7. Calabacillas Arroyo channel bed elevation change – 100-year event, EH transport function, with GCS.

Figure 9 shows the bed elevation changes at three in-phase scenarios: (a) 100-year flood occurs in the MRG with synchronous 100-year storm in the tributary; (b) 25-year flood occurs in the MRG with synchronous 25-year storm in the tributary; (c) 10-year flood occurs in the MRG with synchronous 10-year storm in the tributary. Based on Figure 9 (a) – (c), it can be found that the amount of bed change is mainly determined by sediment input from

the Calabacillas Arroyo. For instance, flood of 100-year storm in the arroyo will bring the most amount of sediment into the main stem of MRG and cause serious deposition problem. The crucial role of sediment source from the tributary can also be revealed when comparing Figure 8 (b) with Figure 9 (a), although the 100-year flood in MRG does mitigate, to a certain extent, the deposition in the main channel. The channel is wide and shallow and the whole channel system is in aggrading.

5. Discussion

To better understand the impact of Calabacillas Arroyo inflow sediment on the evolution of main stream geomorphology, scenarios with equilibrium sediment boundary conditions at Calabacillas Arroyo inlet was also simulated to provide a most extreme conditions.

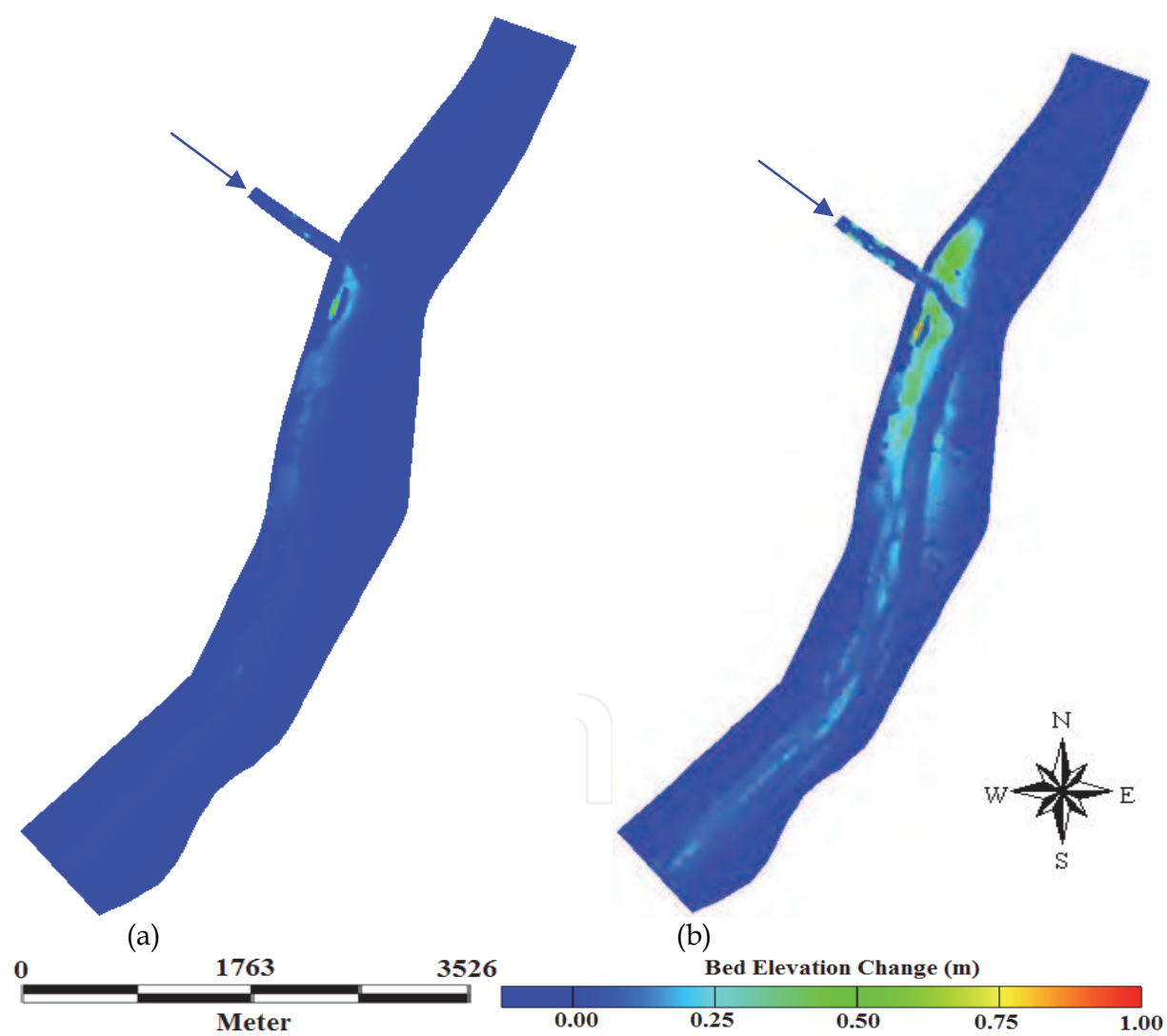


Fig. 8. Bed elevation change after combined flood events: (a) 10-year flood in the tributary with synchronous 100-year flood occurs in the MRG; (b) 100-year flood occurs in the tributary with based flow (25m³/s) in the MRG

Figure 10 shows the bed elevation changes at two scenarios: (a) 100-year flood occurs in the tributary (equilibrium sediment inflow at the Calabacillas Arroyo inlet) with the based flow (25 m³/s) in the MRG; (b) 100-year flood occurs in the MRG with synchronous 100-year flood in the tributary (equilibrium sediment inflow at the upstream boundary of the tributary). The crucial role of sediment source from the tributary can also be revealed when comparing Figure 8b with Figure 10a. There is more inflow sediment from the Calabacillas Arroyo under the equilibrium boundary scenarios which will bring more serious deposition in the main stream. Even the 100-year flood in the MRG has limited ability to flush away the sand bar formed along the right bank. Unlike the non-equilibrium sediment boundary scenarios, the most serious deposition area located just upstream the confluence which indicates stronger ponding effects.

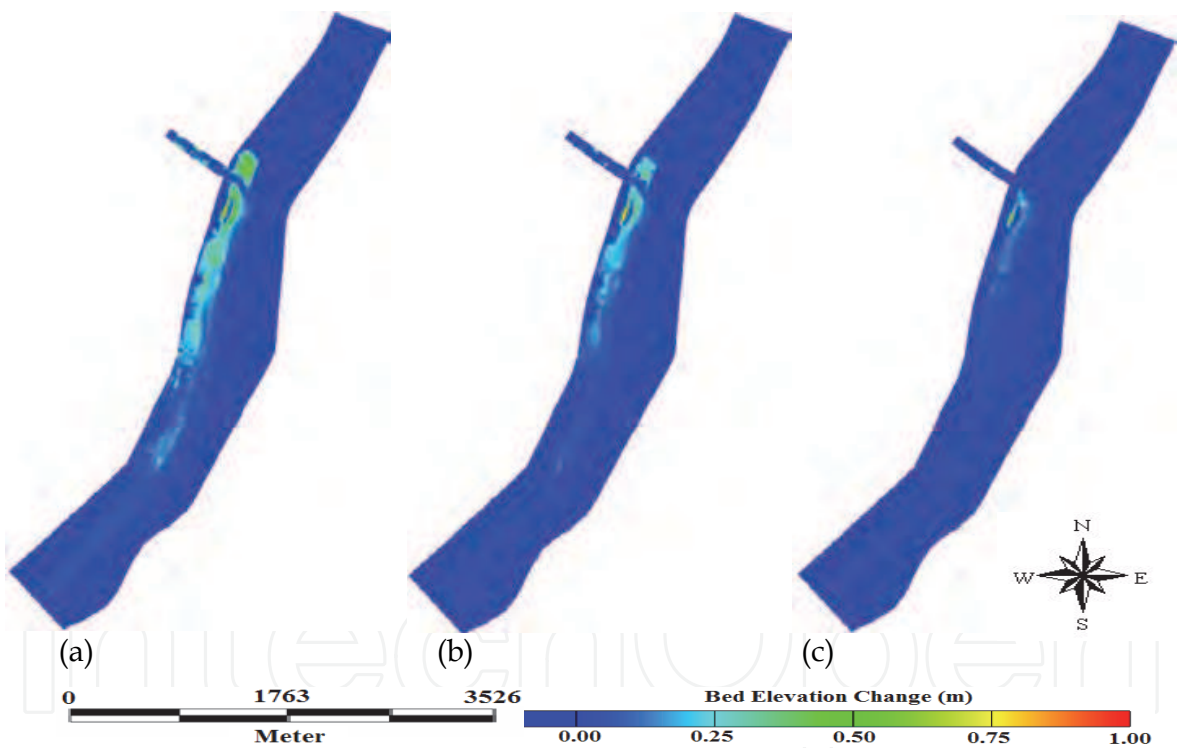


Fig. 9. Bed elevation change after combined flood events: (a) 100-year flood occurs in the MRG with synchronous 100-year flood in the tributary; (b) 25-year flood occurs in the MRG with synchronous 25-year flood in the tributary; (c) 10-year flood occurs in the MRG with synchronous 10-year flood in the tributary

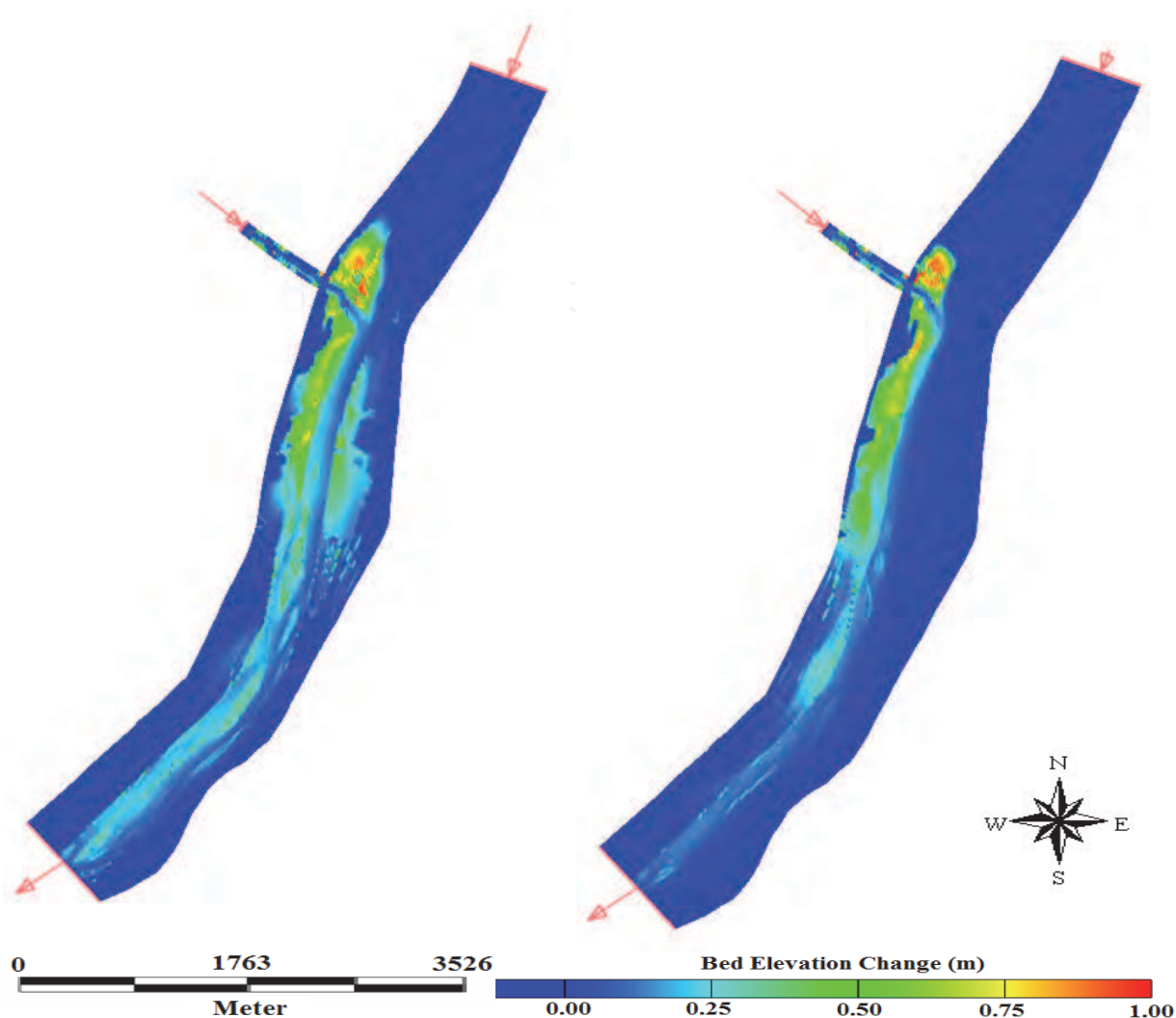


Fig. 10. Bed elevation change after combined flood events: (a) 100-year flood occurs in the tributary (equilibrium sediment inflow at the inlet) with based flow ($25 \text{ m}^3/\text{s}$) in the MRG; (b) 100-year flood occurs in the MRG with synchronous 100-year flood in the tributary (equilibrium sediment inflow at the upstream boundary of the tributary)

6. Conclusions

The Middle Rio Grande (MRG) in Central New Mexico was suffering severe bed aggradation in the history which caused serious flooding problem. Among others, inflow from the Calabacillas Arroyo, a tributary of MRG downstream of the Albuquerque Diversion Dam delivers a large amount of sediment, manifested by the delta formation and the narrowing of the main channel Rio Grande. It implies significant erosion and sediment yield from the surrounding watershed. The goal of this research was to investigate the impact of tributary sediment on the channel geomorphology of main stream MRG.

Three models have been conjunctively applied in this study to conduct a combined investigation of watershed sediment yield, tributary sediment transport, and main channel sedimentation modeling. The following conclusions can be drawn from the study:

1. Significant amount of sediment (7,378 US tons) can be eroded from the watershed and enter the Calabacillas Arroyo channel during a 100-year, 24-hour storm event. However, this portion of the sediment is relatively small compared with the amount of sediment that can be transported to the MRG through Calabacillas Arroyo ;
2. Large amount of sediment (ranging 167,549 - 519,967 US tons) will be scoured from the Calabacillas Arroyo channel to supply the main stream MRG during a 100-year storm event. The GCSs will have limited impact on the sediment transport process under the current situation;
3. According to findings in literature and the current study, EH and Yang sediment transport functions are better applicable for the Calabacillas Arroyo site. MPM function should be used with care because it is limited to bedload prediction;
4. The 25-year and 10-year storms will produce about 60% and 40% of sediment transported by a flood produced by a 100-year storm event, respectively, which are also significant amounts of sediment to the MRG;
5. The sediment input from the Calabacillas Arroyo channel can significantly affect the geomorphic features in the main stream MRG. Serious deposition will happen in the main stream mainly in the downstream reach of the confluence and also in a short reach upstream. The worst situation happens when large events occur in the tributary coincident with low flows in the main stream.

7. Acknowledgement

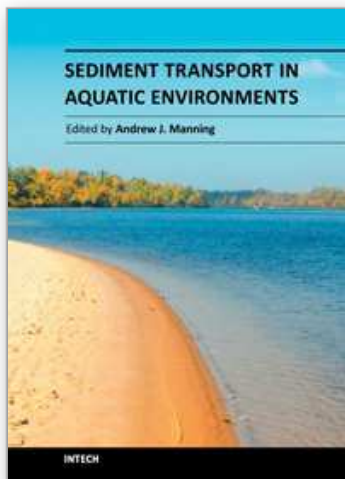
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Sediment Transport in Aquatic Environments is a book which covers a wide range of topics. The effective management of many aquatic environments, requires a detailed understanding of sediment dynamics. This has both environmental and economic implications, especially where there is any anthropogenic involvement. Numerical models are often the tool used for predicting the transport and fate of sediment movement in these situations, as they can estimate the various spatial and temporal fluxes. However, the physical sedimentary processes can vary quite considerably depending upon whether the local sediments are fully cohesive, non-cohesive, or a mixture of both types. For this reason for more than half a century, scientists, engineers, hydrologists and mathematicians have all been continuing to conduct research into the many aspects which influence sediment transport. These issues range from processes such as erosion and deposition to how sediment process observations can be applied in sediment transport modeling frameworks. This book reports the findings from recent research in applied sediment transport which has been conducted in a wide range of aquatic environments. The research was carried out by researchers who specialize in the transport of sediments and related issues. I highly recommend this textbook to both scientists and engineers who deal with sediment transport issues.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

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